4-2018

Possible impacts of a changing climate on intense Ligurian Sea rainfall events

William A. Gallus Jr.
Iowa State University, wgallus@iastate.edu

Antonio Parodi
Centro di Ricerca Interuniversitario in Monitoraggio Ambientale

Maurizio Maugeri
Università degli Studi di Milano

Possible impacts of a changing climate on intense Ligurian Sea rainfall events

Abstract

The region near the Ligurian Sea in northwestern Italy occasionally experiences extreme rainfall events that can lead to catastrophic flooding. These events are often caused by back-building mesoscale convective systems whose occurrence peaks during the autumn. Rapid warming of the Mediterranean Sea in recent decades has raised concerns that the warmer water may change the frequency or intensity of these rainfall events. To gain insight into possible impacts of the warming climate, surface wind and precipitation output from 12-km horizontal grid spacing EXPRESS-Hydro simulations of past and future climate are used to examine trends in the frequency of strong convergence and heavy rainfall events during both the past and the future climate. Strong convergence events are not found to increase in frequency in the future climate, but the rainfall associated with these events does increase. The area that experiences rainfall above a specified threshold along with the duration over which such conditions are experienced increases, especially during the autumn when increases are statistically significant. Peak 3-hourly rainfall at a grid point does not increase in the future climate but total rain volume associated with these events does, reflecting the larger areal coverage and duration of the events.

Keywords

climate, precipitation, flooding, convection, Mediterranean, Liguria

Disciplines

Atmospheric Sciences | Climate

Comments

Full Title: Possible Impacts of a Changing Climate on Intense Ligurian Sea Rainfall Events

Short Title: Impacts of Climate Change on Intense Ligurian Sea Rainfall Events

William A. Gallus, Jr[1]., Antonio Parodi[2], and Maurizio Maugeri[3]

[1]Iowa State University

[2]Centro di Ricerca Interuniversitario in Monitoraggio Ambientale

[3]Università degli Studi di Milano

Corresponding Author: William A. Gallus, Jr., 3025 Agronomy, Iowa State University, Ames, IA, 50011, wgallus@iastate.edu, phone: 1-515-294-2270

Possible Impacts of a Changing Climate on Intense Ligurian Sea Rainfall Events

William A. Gallus, Jr., Antonio Parodi, and Maurizio Maugeri

Abstract:

The region near the Ligurian Sea in northwestern Italy occasionally experiences extreme rainfall events that can lead to catastrophic flooding. These events are often caused by back-building mesoscale convective systems whose occurrence peaks during the autumn. Rapid warming of the Mediterranean Sea in recent decades has raised concerns that the warmer water may change the frequency or intensity of these rainfall events. To gain insight into possible impacts of the warming climate, surface wind and precipitation output from 12-km horizontal grid spacing EXPRESS-Hydro simulations of past and future climate are used to examine trends in the frequency of strong convergence and heavy rainfall events during both the past and the future climate. Strong convergence events are not found to increase in frequency in the future climate, but the rainfall associated with these events does increase. The area that experiences rainfall above a specified threshold along with the duration over which such conditions are experienced increases, especially during the autumn when increases are statistically significant. Peak three-hourly rainfall at a grid point does not increase in the future climate but total rain volume associated with these events does, reflecting the larger areal coverage and duration of the events.

Keywords: Climate, Precipitation, Flooding, Convection, Mediterranean, Liguria

Introduction

Excessive rainfall events are a relatively frequent phenomenon in the northwestern Mediterranean area (e.g., Parodi *et al.*, 2017a), and these events cause substantial loss of life and property every year (Gaume *et al.*, 2009). The most common period for such events is during the autumn when the warm water and favorable large-scale atmospheric conditions (e.g., Reale *et al.*, 2001, Pinto *et al.*, 2013) can result in strong mesoscale convective systems (MCSs) that remain quasi-stationary as they experience back-building (Schumacher and Johnson, 2005, Duffourg *et al.*, 2015, Violante *et al.*, 2016, Fiori *et al.*, 2017, Lagasio *et al.*, 2017). The back-building may be especially favored in parts of this region by the local topography as it encourages convergence of the warm, moist south-easterly flow over the Mediterranean with cooler air from the north that funnels through the relatively low passes of the Apennine mountains in northwestern Italy and to the south into the northern parts of the Ligurian Sea. Ascent induced by the local topography then helps to intensify the rainfall from the MCSs so that it is not uncommon for some locations to receive up to 500 mm or more of rainfall (30-40% of the annual average) in less than a day (Parodi *et al.*, 2012, Fiori *et al.*, 2014, Fiori *et al.*, 2017, Lagasio *et al.*, 2017).

Because these excessive rainfall events are driven by the moisture supplied by both the Atlantic Ocean and the Mediterranean Sea, recent substantial warming of Mediterranean waters at a rate two to three times larger than that for the global oceans (Vargas-Yanez *et al.*, 2008) raises concerns about possible impacts on the frequency and intensity of these events. Flood frequency studies in this region, some going back several centuries, have not yielded consistent results regarding changes in frequency of occurrence (Barriendos *et al.*, 2003, Llasat *et al.*, 2005, Barriendos *et al.*, 2006, Boni *et al.*, 2006, Pinto *et al.*, 2013, Llasat *et al.*, 2014, Toreti *et al.*, 2015). Instead, flood frequency has been found to oscillate from period to period with no significant growth, not even in the most recent decades, regardless of the event's duration (a few hours to days).

Results have also generally been inconclusive regarding climate trends in precipitation extremes over the Mediterranean area in recent decades, (e.g., Brunetti *et al.*, 2001, 2004, Alpert *et al.*, 2002, Kostopoulou and Jones, 2005, Moberg *et al.*, 2006, Brunet *et al.*, 2007, Kioutsioukis *et al.*, 2010, Rodrigo, 2010, Toreti *et al.*, 2010, van den Besselaar *et al.*, 2013). Temporal trends vary across the region (Ulbrich *et al.*, 2012) and are sensitive to the particular site examined, the time period studied, and the approach used (Brugnara *et al.*, 2012, Brunetti *et al.*, 2012, Maugeri *et al.*, 2015). However, climate models do show an increase in precipitation extremes over this region (Alpert *et al.*, 2002, Giorgi and Lionello, 2008, Trenberth, 2011).

The present study uses one set of climate model output to examine temporal changes in the frequency of occurrence and magnitude of events meeting strong convergence and intense rainfall criteria over and near the Ligurian Sea in northwestern Italy. Two 27-year periods are examined, one representing the past climate from 1979-2005, and the other the future climate from 2023-2049. Section 2 discusses the methodology. Results follow in section 3 with conclusions presented in section 4.

1. Methodology

To understand the impact a changing climate might have on the occurrence of heavy rain events near the Ligurian Sea, surface wind (10 m) and 3-hourly precipitation fields from 12-km horizontal grid spacing EXPRESS-Hydro (von Hardenberg *et al.*, 2015, Pieri *et al.*, 2015) Weather Research and Forecasting model (WRF) simulations were examined from two periods: 1979-2005 representing the past climate, and 2023-2049 representing the future climate. For these WRF simulations, Pieri *et al.* (2015) adopted the Kain-Fritsch convective parameterization (Kain, 2004), the Yonsei University Scheme (YSU) planetary boundary layer scheme (Hong *et al.*, 2006), the WRF Single–moment 6–class microphysical scheme (Hong and Lim, 2006), the CAM shortwave and longwave radiation schemes (Chou *et al.*, 1999, and 2001), and the Unified Noah land surface model (Tewari *et al.*, 2004). The past climate was reconstructed with WRF forced by the EC-Earth model using reconstructed historical anthropogenic forcing and solar variability (according to CMIP5 prescriptions), while the scenario for the period 2006–2100 was based on representative concentration pathways (RCPs) for anthropogenic emissions RCP 4.5. RCP 4.5 stabilizes anthropogenic radiative forcing at 4.5 W m–2 (compared to preindustrial) in the year 2100 (Thomson *et al.*, 2011).

Thresholds were applied to several parameters related to heavy rainfall or MCS events. Model output was available every 3 hours and was examined in a rectangular region stretching from 43.5 to 44.5 N and from 7.5 to 10.25 E (Fig. 1). This region is focused over the Ligurian Sea and the nearby coastal regions of northwestern Italy where intense flash-flood producing rainfall has frequently occurred (e.g. Parodi *et al.*, 2012, Rebora *et al.*, 2013, Fiori *et al.*, 2014, Fiori *et al.*, 2017, Lagasio *et al.*, 2017, Parodi *et al.*, 2017a and 2017b).

The parameters examined in the WRF output included convergence of the 10-m wind, convergence accompanied by heavy rainfall, and heavy rainfall alone. For convergence, a land/sea mask was used to eliminate land points from being considered because terrain effects often resulted in localized maxima of low-level convergence not associated with a significant weather system. The following thresholds were used to define the events of interest: (1) convergence exceeding 5.83×10^{-4} s^{-1} at a sea grid point within the box, and this criterion being met for at least two consecutive 3-hourly time periods (not necessarily at the same grid point), (2) the same convergence criterion as in (1) but with 3-hourly rainfall also exceeding 20 mm at the same point meeting the convergence criterion, (3) 3-hourly rainfall exceeding 25 mm at one or more grid points within the box for at least two consecutive 3-hourly time periods, and (4) rain volume within the domain exceeding 2.16×10^{8} m^3 (equivalent to 15 mm or more of rainfall over 100 of the 12 km x 12 km grid boxes) for at least two consecutive 3-hourly time periods. The convergence criterion was based on the threshold used in Parodi *et al.* (2017a) to determine which ensemble members in a WRF-ARW (Advanced Research WRF) ensemble initialized with 56 ensemble members from the 20th Century Reanalysis Project had a signal for the MCS associated with the San Fruttuoso flood event of 1915. However, that threshold was adjusted linearly to account for the difference between the 1 km grid spacing used in that study and the 12 km spacing of the EXPRESS-Hydro output. Parodi *et al.* (2017a) required at least four consecutive hours of strong convergence; thus, in the present study where output are limited to every three hours, two consecutive 3-hour time periods were used. Finally, additional tests were performed using the thresholds described in (2) and (4) but also adding the requirement that the wind direction at either of the two grid points nearest the mountain passes northwest of Savona and north of Genova, respectively, be between 270^{o} and 45^{o} (west through northeast). This additional criterion was added as another constraint to try to isolate the typical MCS events where cool air flows from the Po Plain southward through the Apennines, often enhancing strong convergence over the northern Ligurian Sea.

Analysis was performed using both annual averages and averages for the August-December period alone (hereafter referred to as autumn) when the heaviest rains are usually associated with strong MCSs. An event was defined to be a period up to 30 hours in length when the above criteria were being met, with no more than a 15 hour break between any 3-hour period meeting the criteria. In addition to examining changes in the frequency of these events, statistics were also computed on total number of 3-hourly periods meeting the criteria and the number of grid points meeting the criteria. To determine the statistical significance of differences between the past and future climates, a single-tailed paired Student's t test was performed. In addition, statistical tests were also done using the Mann-Kendall non-parametric test.

2. Results

Strong convergence events per year are found to decrease by 12% in a future climate, from 24.8 to 21.9 (Table 1), and by a similar rate of 13% during the autumn period. The decrease is relatively consistent throughout all months (Fig. 1). Despite the decrease in number of events, the number of occurrences of the criterion (the sum of grid points and 3 hour time periods) increases, by 5% for the year, from 293.2 to 307.8, and by 26.8% for the autumn period, from 132.5 to 168.0 (Table 1). The increase for autumn is statistically significant with 90% confidence in a Student's t test. However, a Mann-Kendall test showed a somewhat higher p value of 0.163. The number of time periods alone does not change appreciably and thus it is the areal coverage of points that increases in the future climate, by 11.4% yearly and 26.5% during autumn. The results suggest that the synoptic setting that allows the strong convergence to occur does not become more frequent and may instead become slightly less common in the future climate, but the events become larger in scale with more grid points exceeding the convergence threshold. It is beyond the scope of this study to explore why the areas of strong convergence become larger, but future work should focus on possible changes to low-level circulation patterns in this region and intensity of low-pressure systems and fronts. The peak average annual 3-hourly value of convergence does not change appreciably from the past climate to the future (not shown), with only a 1% increase in the future climate compared to the past. At first, this result does not appear to support the idea that the increasing number of grid points with convergence above the threshold is due to an intensification of cyclones or fronts. However, it is possible that intensification may not increase the peak magnitude of convergence at any point, which may be more a result of mesoscale factors, but instead allow convergence above the threshold amount to affect a larger region.

To better focus on events that could lead to flooding problems, the second set of criteria were used which included heavy rainfall accompanying strong convergence. For the entire year, no change occurs between the future and past climates (Table 1). However, the monthly distribution (Fig. 3) shows a very large increase during December. With a smaller increase in September, the number of events during the autumn period when heavy precipitation events associated with MCSs are most common increases by 8% (Table 1). Increases in the number of points affected and 3 hour time periods meeting the criteria are much greater, however. During the year, the number of time periods meeting the criteria increases by 13.9%, and during the autumn, by 39%, while the number of grid points affected at a particular time increases by 19.4% over the year, and by 41.6% during autumn. The more widespread nature of events and the greater time consistency or persistence results in a 36% increase in the occurrence of the criteria yearly, and a 97% increase for autumn. This autumn increase is statistically significant with a p-value around 0.025 when using the Student's t test. A Mann-Kendall test applied to the same data also showed statistical significance but with a p-value slightly larger at .0868. An examination of individual years in the past and future climate datasets shows that the peak value in any past year is 37 points meeting the criteria, while in the future climate, one year has 59, with two other years exceeding 50 points.

When the constraint of having winds blow through the Apennine passes toward the Ligurian Sea was added to the criteria of strong convergence accompanied by heavy rain, results do not change noticeably (not shown). The total number of events in the past climate decreased by only three, and by only two in the future climate with this additional constraint. Thus, the majority of the events described above and shown in Table 1 and Figure 3 did occur with the typical low-level flow pattern observed in some documented past events (e.g, Parodi *et al.* 2017a).

To isolate the climate change impacts on rainfall alone, criteria were used that examined both grid point rainfall and total rain volume within the domain. The number of grid points exceeding 25 mm of rainfall in a 3 hour period during a year increases from an average of 135.6 in the past climate to 213.2 in the future climate, an increase of 57% (Table 2). The increase during autumn was even greater, 89%. From Table 2, it can also be seen that the number of grid points meeting the criterion decreases by nearly 10% outside of the autumn, so that the fraction of all grid points meeting the criterion during autumn increases from around 67% during the past climate to 81% during the future climate. Monthly trends (Fig. 4) also indicate this more unequal distribution of heavy rain events in the future climate. Of interest, the average yearly peak grid point rainfall remains roughly unchanged in the future climate at a value of 58.3 mm compared to 58.5 mm in the past climate. The autumn peak values are very similar, which is not surprising since in most years, the peak grid point precipitation amount occurs during autumn.

Finally, the total rain production from these weather systems was evaluated using a rain volume threshold. Large rain volume events increase about 15% in the future climate (Table 3) for the full year, and 32% during the autumn period. Monthly statistics show that the number of events decreases outside the autumn as was true for grid points experiencing heavy rainfall (Fig. 5). The number of 3-hour periods meeting the threshold increases by 43% for the full year, and by 94% for the autumn period, an increase that is statistically significant in both a Student's t test and a Mann-Kendall test with a p-value less than .002. Outside of the autumn period, the number of periods decreases by around 20%. The peak number of times during a year that the criterion is met in the past climate is eight, whereas in the future climate, as many as 17 times meet the criterion in one year (not shown). The mean rain volume for all events meeting the criterion increases by around 10% in the future climate compared to the past climate, both for the full year and for the autumn period alone. Since the peak rainfall at a grid point does not change appreciably, this result indicates that future events become larger in area.

Again, when the additional constraint is applied to require flow through the Apennine passes toward the Ligurian Sea during the large rain volume events, trends do not change substantially (not shown) even though the average annual number of events decreases by 48% in the past climate and 46% in the future climate. Thus, future increases in rain volume are similar in both events that are likely to have characteristics of MCSs influenced by flow through the Apennines and in events that do not share these characteristics. However, the extra constraint relating to wind direction does amplify the change in the future climate when considering the total number of 3-hour periods meeting the rain volume threshold. For the entire year, the increase in the future climate becomes 51% instead of 43%. For autumn alone, the increase in periods becomes 112% instead of 94%. This implies that the events most likely associated with MCSs produce rain volume above the threshold for longer periods of time.

3. Summary and Conclusion

The possible impacts of a warming climate on intense rainfall events near the Ligurian Sea in northwestern Italy have been investigated using 12-km horizontal grid spacing 3-hourly WRF output from the EXPRESS-Hydro project for a past climate and a future climate. The frequency and intensity of events meeting threshold criteria for strong 10-m wind convergence, convergence accompanied by heavy rainfall, intense grid point rainfall, and heavy domain rain volume, were examined over a small rectangular region centered over and near the Ligurian Sea for both 27-year periods. Particular attention was paid to events occurring during the autumn season (defined as August through December) since these events are often associated with back-building MCSs that produce the heaviest rainfall and most severe flooding in the region.

Strong convergence events are not found to increase in frequency or intensity in the future climate, although a small increase occurs in the average number of grid points experiencing strong convergence in the events, particularly during the autumn. A small increase also occurs during autumn for strong convergence events accompanied by heavy rainfall. More notable, however, is the increase that occurs in the future climate in the duration and areal coverage of these events. During autumn, the number of occurrences (grid points at 3-hourly time intervals) nearly doubles in the future climate as the number of grid points meeting the criteria and the number of three hour periods when the criteria are met both increase in comparable amounts.

When thresholds are based on precipitation alone, similar increases in the future climate are observed. The number of occurrences when 3-hourly rainfall at a grid point exceeds 25 mm almost doubles during the autumn. Meanwhile, in the future climate, the number of occurrences meeting this criterion outside of autumn decreases slightly, so that the climatological maximum during autumn becomes more pronounced. Despite more occurrences of heavy rainfall, the average annual peak 3-hourly grid point rainfall does not change appreciably in the future climate. The number of events with intense 3-hourly rain volume undergoes similar changes in the future climate. Events increase substantially during autumn but decrease slightly outside autumn. Bigger changes happen with the number of individual 3-hourly time periods meeting the criterion, which nearly doubles during autumn while decreasing roughly 20% in the rest of the year. The average annual peak 3-hourly rain volume does increase by 10% in the future climate, despite the lack of an increase in the average annual peak grid point 3-hourly value. This result is consistent with the other findings that future rainfall events will cover larger areas and persist over longer time periods.

The results of this study have implications for emergency managers in this region, as they suggest a likelihood for broader and potentially more serious impacts from future intense rainfall events. The frequency of the events may not increase noticeably, but because heavy rainfall is likely to affect larger areas over longer time periods, the situation may be different considering specific grid points where the probability of heavy amounts would increase. This would result in higher return levels within specified time intervals at point locations, increasing the risk of flooding in even very small catchments.

Future work should focus on the use of finer grid model output of future climate as it becomes available. The types of events studied here often consist of very fine-scale convective structures that are not well-resolved by the use of 12-km horizontal grid spacing output (e.g., Wesiman *et al.* 1997). The use of convection-allowing grid spacings would remove the need for convective parameterization that is known to introduce potentially substantial errors into simulations (e.g., Gallus, 1999; Jankov *et al.*, 2005).

Acknowledgments

The lead author appreciates the opportunity to have visited the Department of Physics at the Universita' degli Studi di Milano during a Faculty Professional Development Assignment in autumn 2016, when much of this work was begun.

References

Alpert, P, Ben-Gai, T, Baharad, A, Benjamini, Y, Yekutieli, D, Colacino, M, Diodato, L, Ramis, C, Homar, V, Romero, R, Michaelides, S, Manes, A. 2002. The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total values. *Geophys. Res. Lett.* **29(11)**. doi:10.1029/2001GL013554.

Barriendos, M, Coeur, D, Lang, M, Llasat, MC, Naulet, R, Lemaître, D, Barrera, A. 2003. Stationarity analysis of historical flood series in France and Spain (14th–20th centuries). *Natural Hazards and Earth System Science* **3(6)**: 583-592.

Barriendos, M, Rodrigo, FS. 2006. Study of historical flood events on Spanish rivers using documentary data. *Hydrological Sciences Journal* **51(5)**: 765-783.

Boni, G, Parodi, A, Rudari, R. 2006. Extreme rainfall events: Learning from raingauge time series. *Journal of Hydrology* **327(3)**: 304-314.

Brugnara, Y, Brunetti, M, Maugeri, M, Nanni, T, Simolo, C. 2012. High-resolution analysis of daily precipitation trends in the central Alps over the last century. *International Journal of Climatology* **32(9)**: 1406-1422.

Brunet, M, Jones, PD, Sigró, J, Saladié, O, Aguilar, E, Moberg, A, Della-Marta, PM, Lister, D, Walther, A, López, D. 2007. Temporal and spatial temperature variability and change over Spain during 1850–2005. *Journal of Geophysical Research: Atmospheres* **112:** D12117, doi:10.1029/2006JD008249.

Brunetti, M, Maugeri, M, Nanni, T. 2001. Changes in total precipitation, rainy days and extreme events in northeastern Italy. *International Journal of Climatology* **21(7)**: 861-871.

Brunetti, M, Buffoni, L, Mangianti, F, Maugeri, M, Nanni, T. 2004. Temperature, precipitation and extreme events during the last century in Italy. *Global and Planetary Change* **40(1):** 141-149.

Brunetti, M, Caloiero, T, Coscarelli, R, Gullà, G, Nanni, T, Simolo, C. 2012. Precipitation variability and change in the Calabria region (Italy) from a high resolution daily dataset. *International Journal of Climatology* **32(1)**: 57-73.

Chou, MD, Suarez, MJ. 1999. A solar radiation parameterization for atmospheric studies. *NASA Tech. Memo*. *104606* **15**: 40 pp.

Chou, MD, Suarez, MJ, Liang, XZ, Yan, MMH. 2001. A thermal infrared radiation parameterization for atmospheric studies. *NASA Tech. Memo., 104606* **19:** 68 pp.

Duffourg, F, Nuissier, O, Ducrocq, V, Flamant, C, Chazette, P, Delanoe, J, Doerenbecher, A, Fourrié, N, Di Girolamo, P, Lac, C, Legain, D, Martinet, M, Said, F, Bock, O, Legain, D. 2015. Offshore deep convection initiation and maintenance during I0P16a Offshore deep convection initiation and maintenance during HyMeX IOP 16a heavy precipitation event. *Quarterly Journal of the Royal Meteorological Society* **142**: 259–274.

Fiori, E, Comellas, A, Molini, L, Rebora, N, Siccardi, F, Gochis, DJ, Tanelli, S, Parodi, A. 2014. Analysis and hindcast simulations of an extreme rainfall event in the Mediterranean area: The Genoa 2011 case. *Atmospheric Research* **138**: 13-29.

Fiori, E., Ferraris, L., Molini, L., Siccardi, F., Kranzlmueller, D., & Parodi, A. 2017. Triggering and evolution of a deep convective system in the Mediterranean Sea: modelling and observations at a very fine scale. *Quarterly Journal of the Royal Meteorological Society* **143(703)**: 927-941.

Gallus, Jr., WA. 1999. Eta simulations of three extreme precipitation events: Impact of resolution and choice of convective parameterization. *Wea. and Forecasting* **14:** 405-426.

Gaume, E, Bain, V, Bernardara, P, Newinger, O, Barbuc, M, Bateman, A, Blaškovicová, L, Blöschl, G, Borga, M, Dumitrescu, A, Daliakopoulos, J, Garcia, J, Irimescu, A, Kohnova, S, Koutroulis, A, Marchi, L, Matreata, S, Medina, V, Preciso, E, Sempere-Torres, D, Stancalie, G, Szolgay, J, Tsanis, J, Velascom, D, Viglione, A. 2009. A compilation of data on European flash floods. *Journal of Hydrology* **367(1)**: 70-78.

Giorgi, F., Lionello, P. 2008. Climate change projections for the Mediterranean region. *Global and Planetary Change* **63(2)**: 90-104.

Hong, S–Y, Lim, J-OJ. 2006. The WRF single–moment 6–class microphysics scheme (WSM6). *J. Korean Meteor. Soc*. **42**: 129–151.

Hong, S-Y, Noh, Y, Dudhia, J. 2006. A new vertical diffusion package with an explicit treatment of entrainment processes. *Mon. Wea. Rev*. **134**: 2318–2341.

Jankov, I, Gallus, Jr., WA, Shaw, B, Koch, SE. 2005. On the impacts of different physical parameterizations and their interactions on warm season MCS rainfall. *Wea. Forecasting* **20**: 1048-1060.

Kain, JS. 2004. The Kain–Fritsch convective parameterization: An update. *J. Appl. Meteor*. **43**: 170–181.

Kioutsioukis, I, Melas, D, Zerefos, C. 2010. Statistical assessment of changes in climate extremes over Greece (1955–2002). *International Journal of Climatology* **30(11)**: 1723-1737.

Kostopoulou, E, Jones, PD. 2005. Assessment of climate extremes in the Eastern Mediterranean. *Meteorology and Atmospheric Physics* **89(1-4)**: 69-85.

Lagasio, M, Parodi, A, Procopio, R, Rachidi, F, Fiori, E. 2017. Lightning Potential Index performances in multimicrophysical cloud-resolving simulations of a back-building mesoscale convective system: The Genoa 2014 event. *Journal of Geophysical Research: Atmospheres* **122(8)**: 4238-4257, doi:10.1002/2016JD026115.

Llasat, MC, Barriendos, M, Barrera, A, Rigo, T. 2005. Floods in Catalonia (NE Spain) since the 14th century. Climatological and meteorological aspects from historical documentary sources and old instrumental records. *Journal of Hydrology* **313(1)**: 32-47.

Llasat, MC, Marcos, R, Llasat-Botija, M, Gilabert, J, Turco, M, Quintana-Seguí, P. 2014. Flash flood evolution in North-Western Mediterranean. *Atmospheric Research* **149**: 230-243.

Maugeri, M, Brunetti, M, Garzoglio, M, Simolo, C. 2015. High-resolution analysis of 1 day extreme precipitation in Sicily. *Natural Hazards and Earth System Science* **15(10)**: 2347-2358.

Moberg, A, Jones, PD, Lister, D, Alexander, W, Brunet, M, Jacobeit, J, Alexander, LV, Della-Marta, PM, Luterbacher, J, Yiou, P, Chen, D, Klein Tank, AMG, Saladié, O, Sigró, J, Aguilar, E, Alexandersson, H, Almarza, C, Auer, I, Barriendos, M, Begert, M, Bergström, H, Böhm, R, Butler, CJ, Caesar, J, Drebs, A, Founda, D, Gerstengarbe, FW, Micela, G, Maugeri, M, Österle, H, Pandzic, K, Petrakis, M, Srnec, L, Tolasz, R, Tuomenvirta, H, Werner, PC, Linderholm, H, Philipp, A, Wanner, H, Xoplaki, E. 2006. Indices for daily temperature and precipitation extremes in Europe analyzed for the period 1901–2000. *Journal of Geophysical Research: Atmospheres* **111**: D22106.

Parodi, A, Boni, G, Ferraris, L, Siccardi, F, Pagliara, P. Trovatore, E, Foufoula-Georgiou, E, Kranzlmueller, D. 2012. The “perfect storm”: From across the Atlantic to the hills of Genoa. *Eos, Transactions American Geophysical Union* **93(24)**: 225-226.

Parodi, A, Ferraris, L, Gallus, Jr., WA, Maugeri, M, Molini, L, Siccardi, F, Boni G. 2017a. Ensemble cloud-resolving modeling of a historic back-building mesoscale convective system over Liguria: The San Fruttuoso case of 1915. *Climate of the Past* **13:** 455-472. doi:10.5194/cp-13-455-2017.

Parodi, A, Kranzlmueller, D, Clematis, A, Danovaro, E, Galizia, A, Garrote, L, Llasat, M, Caumont, O, Richard, E, Harpham, Q, Siccardi, F, Ferraris, L, Rebora, N, Delogu, F, Fiori, E, Molini, L, Georgiou, E, D'Agostino, D. 2017b. DRIHM(2US): an e-Science environment for hydro-meteorological research on AMERICAN METEOROLOGICAL SOCIETY high impact weather events. *Bull. Amer. Meteor. Soc*. doi:10.1175/BAMS-D-16- 0279.1, in press.

Pieri, AB, von Hardenberg, J, Parodi, A, Provenzale, A. 2015. Sensitivity of precipitation statistics to resolution, microphysics, and convective parameterization: A case study with the high-resolution WRF climate model over Europe. *Journal of Hydrometeorology* **16(4):** 1857-1872.

Pinto, JG, Ulbrich, S, Parodi, A, Rudari, R, Boni, G, Ulbrich, U. 2013. Identification and ranking of extraordinary rainfall events over Northwest Italy: The role of Atlantic moisture. *Journal of Geophysical Research: Atmospheres* **118(5)**: 2085-2097.

Reale, O, Feudale, L, Turato, B. 2001. Evaporative moisture sources during a sequence of floods in the Mediterranean region. *Geophysical research Letters* **28(10)**: 2085-2088.

Rebora, N, Molini, L, Casella, E, Comellas, A, Fiori, E, Pignone, F, Siccardi, F, Silvestro, F, Tanelli, S, Parodi, A. 2013. Extreme rainfall in the mediterranean: what can we learn from observations?. *Journal of Hydrometeorology* **14(3)**: 906-922.

Rodrigo, FS. 2010. Changes in the probability of extreme daily precipitation observed from 1951 to 2002 in the Iberian Peninsula. *International Journal of Climatology* **30(10)**: 1512-1525.

Schumacher, RS, Johnson, RH. 2005. Organization and environmental properties of extreme-rain-producing mesoscale convective systems. *Monthly Weather Review* **133(4)**: 961-976.

Tewari, M, Chen F, Wang, W, Dudhia, J, LeMone, MA, Mitchell, K, Ek, M, Gayno, G, Wegiel, J, Cuenca, RH. 2004. Implementation and verification of the unified NOAH land surface model in the WRF model. *20th conference on weather analysis and forecasting/16th conference on numerical weather prediction*, pp. 11–15.

Thomson, AM, Calvin, KV, Smith, SJ, Kyle, GP, Volke, A, Patel, P, ...Edmonds, JA. 2011. RCP4. 5: a pathway for stabilization of radiative forcing by 2100. *Climatic Change* **109(1-2):** 77.

Toreti, A, Xoplaki, E, Maraun, D, Kuglitsch, FG, Wanner, H, Luterbacher, J. 2010. Characterisation of extreme winter precipitation in Mediterranean coastal sites and associated anomalous atmospheric circulation patterns. *Nat. Hazards Earth Syst. Sci* **10(5)**: 1037-1050.

Toreti, A., Giannakaki, P., & Martius, O. 2015. Precipitation extremes in the Mediterranean region and associated upper-level synoptic-scale flow structures. Climate Dynamics, 1-17.

Trenberth, KE. 2011. Changes in precipitation with climate change. *Climate Research* **47(1)**: 123.

Ulbrich, U, Lionello, P, Belušić, D, Jacobeit, J, Knippertz, P, Kuglitsch, FG, Leckebusch, GC, Luterbacher, J, Maugeri, M, Maheras, P, Nissen, KM, Pavan, V, Pinto, JG, Saaroni, H, Seubert, S, Toreti, A, Xoplaki, E, Ziv, B. 2012. Climate of the Mediterranean: synoptic patterns, temperature, precipitation, winds, and their extremes. In *The Climate of the Mediterranean Region-From the Past to the Future*. Elsevier, London.

Van den Besselaar, EJ, Klein, M, Tank, AMG, Buishand, TA. 2013. Trends in European precipitation extremes over 1951–2010. *International Journal of Climatology* **33(12)**: 2682-2689.

Vargas-Yanez, M, Garcia, MJ, Salat, J, Garcia-Martinez, MC, Pascual, J, Moya F. 2008. Warming trends and decadal variability in the Western Mediterranean shelf. *Glob. Planet. Chang*. **63**: 177-184.

Violante, C, Braca, G, Esposito, E, Tranfaglia, G. 2016. The 9 September 2010 torrential rain and flash flood in the Dragone catchment, Atrani, Amalfi Coast (southern Italy). *Natural Hazards and Earth System Sciences* **16(2)**: 333-348.

von Hardenberg, J, Parodi, A, Pieri, AB, Provenzale, A. 2015. Impact of Microphysics and Convective Parameterizations on Dynamical Downscaling for the European Domain. *In Engineering Geology for Society and Territory-Volume 1* (pp. 209-213). Springer International Publishing.

Weisman, ML, Skamarock, WC, Klemp, JB. 1997. The resolution dependence of explicitly modeled convective systems. *Mon. Wea. Rev.* **125**: 527-548.

Table 1: Average number of events, 3 hour time periods, grid points, and occurrences (sum of all grid points and times) meeting the convergence threshold and the convergence threshold combined with the heavy rainfall threshold for the past and future climate for the entire year, and the autumn period (August-December).

	Conv. Events	Conv. Periods	Conv. Points	Conv. Occur.	Conv. + Precip. Events	Conv. + Precip. Periods	Conv. + Precip. Points	Conv. + Precip. Occur.
Year (past)	24.8	65.2	4.39	286	2.35	4.31	4.13	17.8
Year (future)	21.9	62.7	4.89	307	2.35	4.91	4.93	24.2
Autumn (past)	11.5	31.3	4.23	132	1.46	2.54	3.58	9.09
Autumn (future)	10.0	31.4	5.35	168	1.58	3.53	5.07	17.9

Table 2: Grid points meeting the heavy rain threshold in past and future climates for the entire year and autumn alone, along with average annual peak grid point amount (mm).

	Grid points	Average peak amount
Year (past)	136	58.5
Year (future)	213	58.3
Autumn (past)	91.4	56.5
Autumn (future)	173	57.0

Table 3: Average number of events when rain volume threshold was met for the domain in past and future climates for the entire year and for autumn alone, with average number of 3-hour periods and average annual peak volume (km^3) for events meeting the criteria (for a few years in the past climate, the threshold was lowered to provide a peak volume value, since no events met the original threshold).

	Events	Periods	Average Peak Volume
Year (past)	3.41	5.03	73.4
Year (future)	3.93	7.20	80.8
Autumn (past)	2.19	2.81	68.6
Autumn (future)	2.88	5.44	78.6

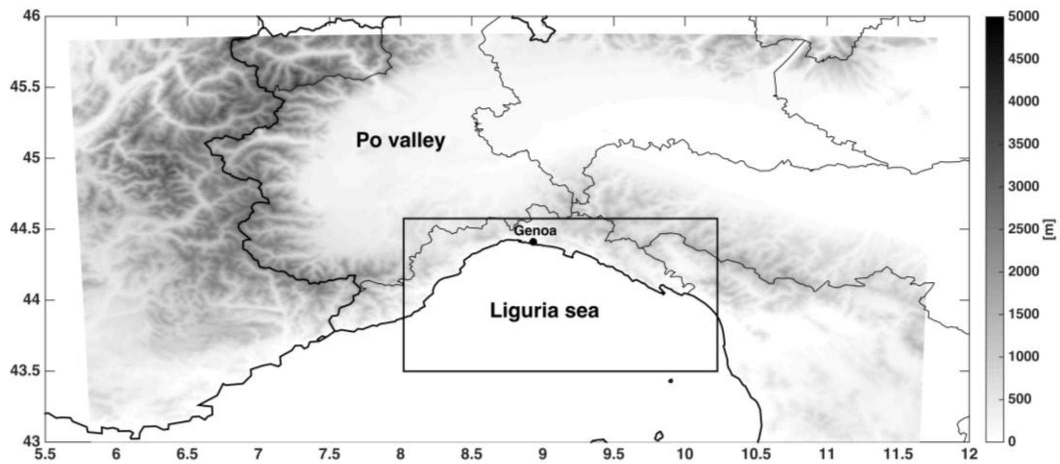

Figure 1: Ligurian Sea region with the polygon used for the present study indicated with a box. Terrain heights indicated with gray shading (meters).

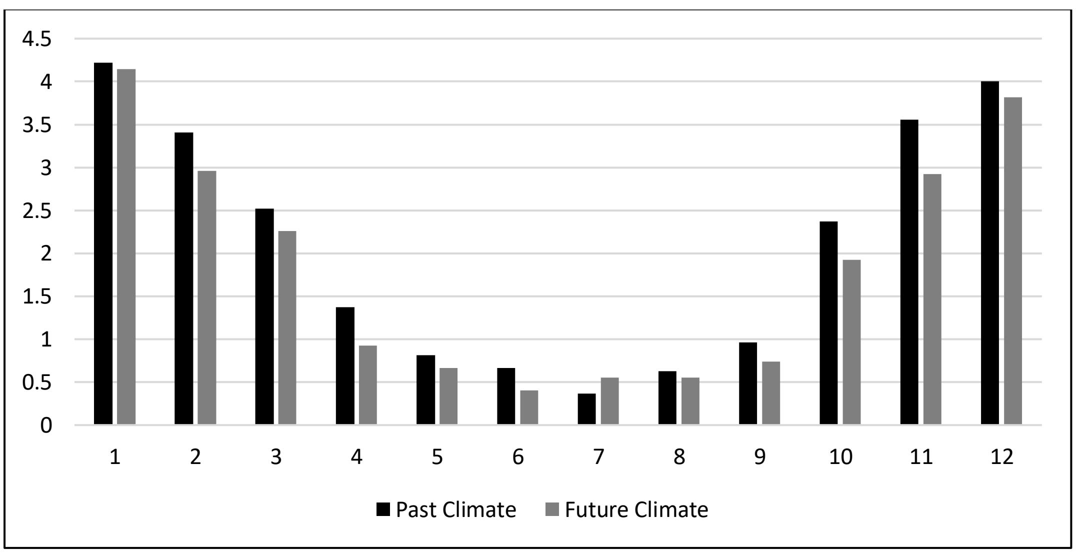

Figure 2: Average number of events per month in the past and future climates meeting the strong convergence criteria defined in the text.

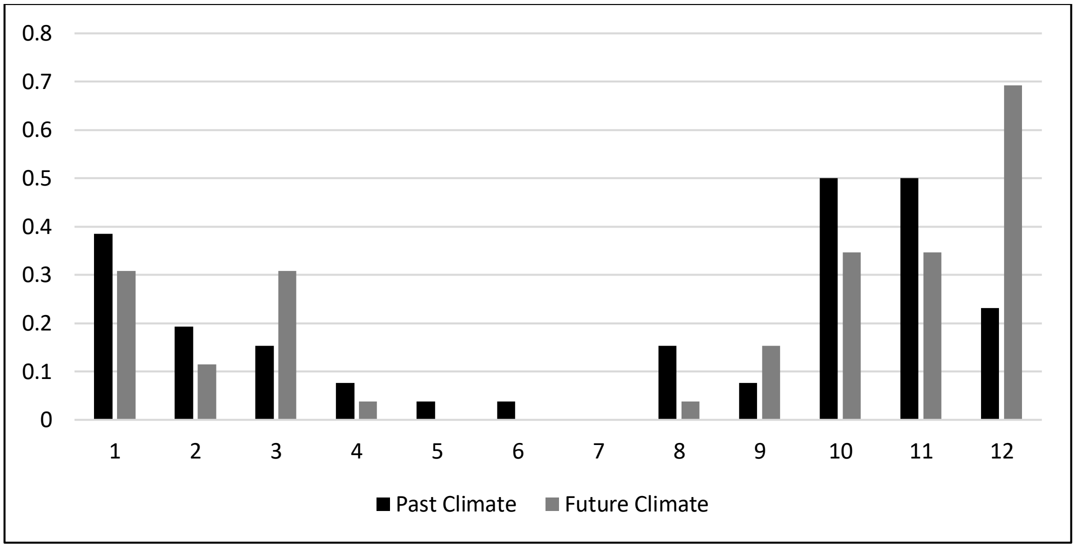

Figure 3: As in Figure 2 but for events meeting the strong convergence and heavy rain criteria.

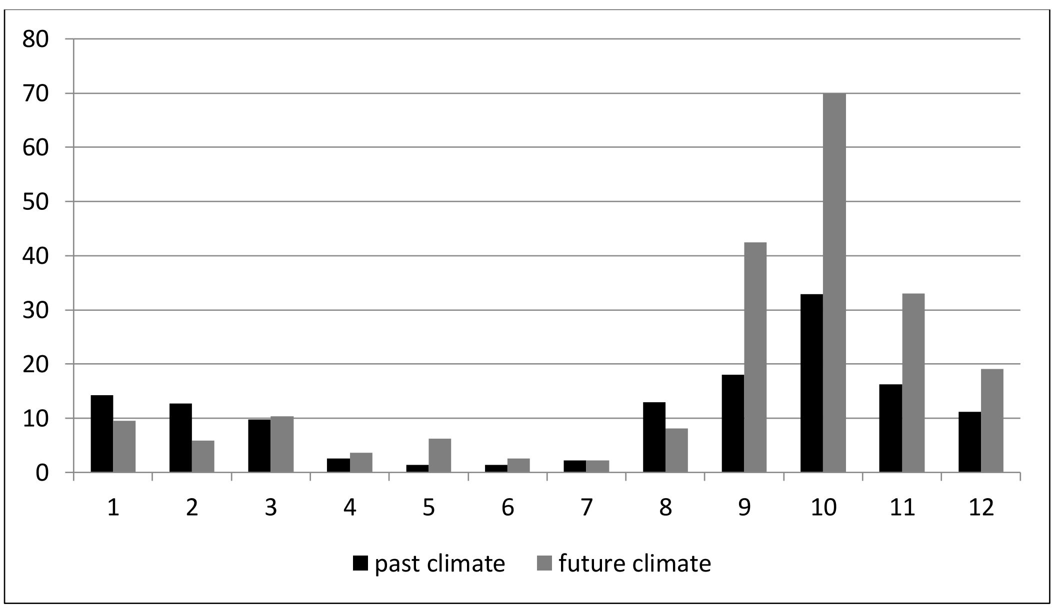

Figure 4: As in Figure 2 but for the number of grid points exceeding 25 mm of rain in a 3 hour period.

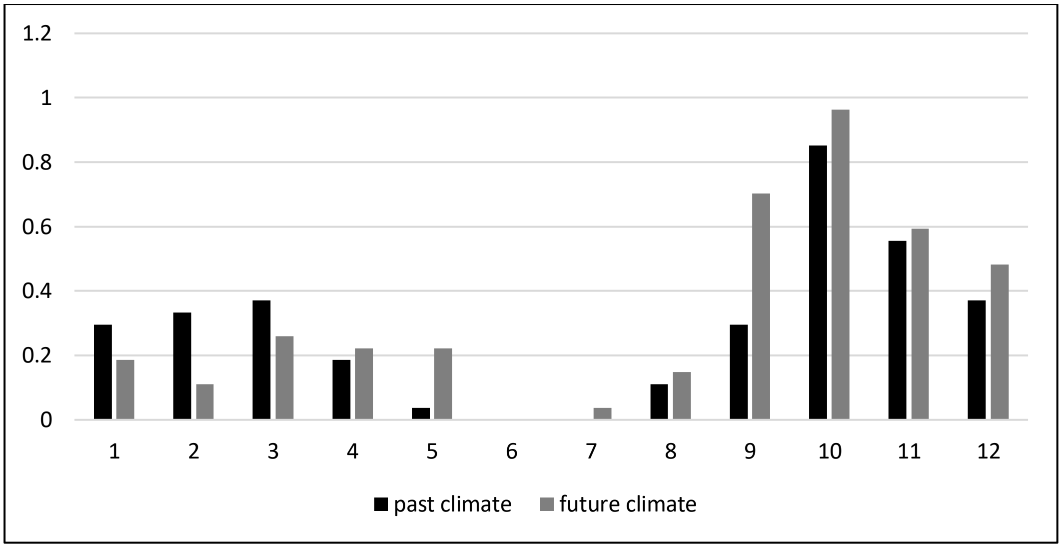

Figure 5: As in Figure 2 but for the number of 3 hour time periods with rain volume exceeding a value equivalent to 100 grid points having 15 mm of rain each.